Open Access

Review Article

J. Glob. Innov. Agric. Sci., 2026, 14(2):321-346
ISSN (Online): 2788-4546; ISSN (Print):2788-4538
DOI: https://doi.org/10.22194/JGIAS/26.1964
http://www.jgiass.com

Chitosan-Based Coatings for Fruit Preservation: A Bibliometric Study and Evidence of Shelf-Life Extension

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Post-harvest fruit losses threaten food security. We conducted a PRISMA-guided bibliometric mapping and descriptive synthesis of shelf-life outcomes. A Scopus search on 10 June 2025 (original research, English, final versions) yielded 1,087 articles (1993–2025). Two reviewers screened titles/abstracts and full texts. Scientific mapping (Bibliometrix, VOSviewer) shows output rising since 2017, with the latest period (2017–2025) contributing 864/1,087 records (~79%) and 21,891 citations. China leads production and international collaboration. Research concentrates on strawberry, mango, tomato, grape and papaya. Shelf life was harmonised to days; within each study we extracted paired values for chitosan-treated fruit and its matched control under identical storage. Illustrative pairs show Citrus × sinensis 30.9 vs 17.5 days, Pyrus communis 21.4 vs 7.0, and Vaccinium spp. 14.8 vs 5.7. Formulations with essential oils (n=90) and metallic nanoparticles (n=89) were the most frequently investigated and were often associated with longer shelf life and antifungal/antioxidant effects in individual studies. Overall, chitosan coatings emerge as a bio-based, biodegradable and widely investigated approach to mitigating post-harvest losses.

Keywords: Biocontrol; chitosan; antifungal; food loss mitigation; fruit.

INTRODUCTION

An alarming proportion of fruit is wasted globally after harvest. Around 14% of global production is lost from harvest to sale to the consumer. These losses have economic implications for producers and supply chains, while exacerbating food insecurity in a world (FAO, 2019a).
Beyond the economic costs, food loss and waste involve the use of land, water, and energy and are estimated to account for 8–10% of global anthropogenic GHG emissions (FAO, 2019b; Yumbya et al., 2025). Therefore, reducing post-harvest fruit losses represents not only an economic opportunity but also a key strategy to mitigate the environmental impact of agriculture and improve food availability (FAO, 2022; Springmann et al., 2018). This global context has motivated the search for sustainable post-harvest technologies to preserve fruit quality and reduce such losses. Chitosan is a promising biotechnological tool for postharvest fruit preservation due to its physicochemical and biological properties. Derived from the deacetylation of chitin, chitosan is a biodegradable, non-toxic, natural polysaccharide that is safe for consumers and the environment (Rinaudo, 2006). In the United States, some chitosan preparations have obtained GRAS (Generally Recognized as Safe) designation from the FDA (United States Food and Drug Administration) for specific uses; approvals and

Feijoo, R.J.H., Rodriguez, J.A.T., Patiño, M.S.C., Ortiz, C.C., Rivera, S.G., Toulkeridis, T., & Montiel, L.G.H. (2026). Chitosan-Based Coatings for Fruit Preservation: A Bibliometric Study and Evidence of Shelf-Life Extension. *Journal of Global Innovations in Agricultural Sciences*, *14*(2),321-346.
[Received 11 Sep 2025; Accepted 24 Dec 2025; Published 11 Jan 2026]
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regulatory conditions vary by jurisdiction and application (e.g., direct food additive, processing aid, packaging/coating) (Romanazzi et al., 2017).

Chitosan exhibits direct antimicrobial action, inhibiting the growth of phytopathogenic fungi and rot-causing bacteria through electrostatic interactions with the anionic cell surface of microorganisms, due to its cationic nature (Wang et al., 2024a). In addition, it acts as an elicitor: recognition of chitosan activates early signals (Ca^{2+} influx, MAPK cascades, and oxidative burst of ROS) that precede and give rise to subsequent responses, including the induction of PR proteins (PR-2 β-1,3-glucanases; PR-3/PR-4 chitinases), increased antioxidant capacity, and, depending on the species, the accumulation of phytoalexins (Petriccione et al., 2015a; Safari et al., 2021). Chitosan forms a semipermeable film on fruits that reduces gas exchange, slows respiration and transpiration, and delays ripening and senescence processes (Popescu et al., 2022; Shah & Hashmi, 2020).

Unlike common synthetic coatings used after harvest (e.g., polyvinyl alcohol (PVA) or polyethylene (PE)), which act primarily as inert barriers defined by their thickness and crystallinity (Clark et al., 2014; Jasse et al., 1994), chitosan films provide active sites and exhibit gas and water vapor permeability that is sensitive to molecular weight and degree of deacetylation (Gomes et al., 2018; Jiménez-Gómez & Cecilia, 2020). Under typical fruit storage conditions (4–12 °C; high relative humidity), these films maintain their integrity for days or weeks (Ls et al., 2018); after removal, the polymer is susceptible to hydrolysis and enzymatic biodegradation (e.g., by chitinases/lysozyme), with rates modulated by molecular weight and degree of deacetylation (Freier et al., 2005; Szymańska & Winnicka, 2015).

The versatility of chitosan as a film-forming matrix allows the incorporation of various bioactive and nanotechnological additives to enhance its preservative efficacy. A common strategy is the addition of essential oils (EOs) extracted from aromatic plants (e.g., thyme, cinnamon, clove), which confer additional antimicrobial and antioxidant properties to the coating (Chen et al., 2025; Putra et al., 2025). In addition, nanocomposites have been developed with a chitosan matrix and dispersed inorganic nanoparticles (e.g., ZnO, Ag, TiO_2), as well as chitosan nanoparticles (QNPs), polymeric structures obtained by ionic gelation/self-assembly, used to encapsulate bioactives and modulate their release (Bui et al., 2025; Sani et al., 2025; Wang et al., 2023). Both chitosan coatings with essential oils (free or nanoformulated) and chitosan–inorganic NPs nanocomposites account for a large part of recent literature.

The efficacy of chitosan has been demonstrated in a wide range of fruits. Among these, trials on banana (*Musa spp.*), mango (*Mangifera indica* L.), strawberry (*Fragaria* × *ananassa* Duch.) and tomato (*Solanum lycopersicum* L.), have been successful in reducing weight loss, delaying softening, and controlling diseases such as anthracnose and fruit rot caused by *Colletotrichum* spp. and *Botrytis* spp (Jalal et al., 2024; Mahin et al., 2025; Nitikornwarakul et al., 2024; Roidoung et al., 2025). However, despite extensive research, chitosan coatings have limitations. Their performance depends largely on the characteristics of the polymer (molecular weight, degree of deacetylation), the solvent/acid system, and the physiology of the fruit surface, which reduces comparability between studies (Rinaudo, 2006; Romanazzi et al., 2018). Sensory acceptance can be affected by viscosity, stickiness, or aroma, especially in formulations with essential oils, so the dosage and thickness must be optimized for each product and storage condition (Martínez et al., 2018a; Valenzuela et al., 2015).

Specifically, this study aims to (i) quantify the annual evolution of scientific production (RQ1); (ii) map productivity by country and co-authorship networks (RQ2–RQ3); (iii) characterize leading institutions (RQ4); (iv) identify the journals that concentrate their publication (RQ5); (v) recognize the most influential articles and highlight the methodological/technological features associated with their impact (RQ6); (vi) map the intellectual structure through keyword co-occurrence clusters (RQ7); (vii) determine the fruits with the greatest research attention (RQ8); and, based on experimental evidence, (viii) demonstrate how chitosan extends shelf life compared to the control (RQ9) and (ix) compare the efficacy of the main chitosan-based combinations (RQ10).

MATERIALS ANSD METHODS

The bibliometric analysis was developed following the PRISMA protocol (Preferred Reporting Items for Systematic Reviews and Meta-Analyses), recognized for providing a structured, efficient and transparent approach to the evaluation of scientific literature (Page et al., 2021). In this study, the methodological process was organized into two main stages: (1) application of search and eligibility criteria; and (2) interpretation and analysis of the collected data.

Search criteria and eligibility: Document collection was conducted from the Scopus database, due to its high multidisciplinary coverage, metadata reliability, and compatibility with bibliometric software. The search was executed on June 10, 2025, using the following equation in the advanced search field:

(TITLE-ABS-KEY (fruit*) AND TITLE-ABS-KEY ("post-harvest" OR "postharvest" OR shelf OR "bio-control" OR biocontrol) AND TITLE-ABS-KEY (coat* OR (film AND (bio OR edible OR composite))) AND TITLE-ABS-KEY (chitosan))).

For document selection, inclusion criteria were established that considered exclusively original scientific articles published in English and in final publication status. In contrast, reviews, conference papers, book chapters, erratums, short surveys, conference reviews, books, and data papers

were excluded. Once these filters were applied, a total of 1,087 scientific articles were obtained, which were exported in CSV format for bibliometric analysis and BibTeX for reference management.

Based on the above, the search criteria were aimed at answering the following research questions (RQ):

RQ1. How does scientific production on chitosan in postharvest fruit evolve annually?

RQ2. Which countries have the highest productivity?

RQ3. Which countries have the most intense co-authorship and collaboration networks?

RQ4. Which institutions lead in terms of publication volume and impact, and what are their specializations?

RQ5. In which journals are the articles published and where is the greatest impact in the field concentrated?

RQ6. Which are the most influential articles, and what methodological/technological features explain their leadership?

RQ7. What thematic clusters emerge from the keyword co-occurrence analysis?

RQ8. Which fruits dominate the research body?

RQ9. To what extent does chitosan extend postharvest shelf life (days vs. control)?

RQ10. Which combinations with chitosan are most effective?

2.2. Data interpretation

***Temporal evolution of scientific production (RQ1)*:** To implement this process, the CSV file was used in Microsoft Excel, where a pivot table was created to count the number of documents published per year and total annual citations. The results were then grouped into defined periods to identify temporal trends. The processed information was used to generate evolution graphs in R, using the following packages: ggplot2, scales, tidyr, and dplyr.

***Geographical distribution by country (RQ2)*:**

The identification of the number of publications by country of affiliation was conducted using the Bibliometrix package in the RStudio environment (Aria & Cuccurullo, 2017). The extracted data were processed and geographically mapped in ArcMap 10.5, generating a map that reflects the intensity of scientific production by country.

Co-authorship and scientific collaboration networks (RQ3): The cross-country collaboration network was constructed using the Bibliometrix co-authorship analysis module, considering links by country of affiliation. With the information processed in Excel, a chord diagram was created in R using the following packages: dplyr, circlize, and RColorBrewer.

More productive institutions (RQ4):The data were extracted from the Scopus Affiliation tab. A bar graph indicating the institutions with the highest number of publications was then generated using the ggplot2 package in R.

Most relevant scientific journals (RQ5):The scientific journals with the highest number of publications were identified using the Source title field of the CSV file exported from Scopus. For each journal, five bibliometric indicators were compiled: the total number of contributions, the quartile, the SJR (Scimago Journal Rank), and the H-index, obtained from the Scimago Journal & Country Rank portal, as well as the most recent impact factor (IF), reported by the Journal Citation Reports (JCR).

2.2.6. Most cited articles (RQ6)

The articles were ranked according to the "Cited by" (highest) criteria within the Scopus platform. A list of the most influential documents was compiled based on the total number of citations, year of publication, subject area, and country of origin.

***Keyword co-occurrence analysis (RQ7)*:** The CSV file was used in VOSviewer software, selecting the author keyword co-occurrence analysis. A minimum frequency threshold was set (≥3 occurrences).

***Most studied fruits (RQ8*):** A manual review of each retrieved article was conducted to identify the species or group of fruits studied. The information was organized in Excel, and a bar graph was created in R (ggplot2) to demonstrate the frequency of occurrence of each fruit in the set of studies.

***Effect of chitosan on postharvest shelf life (RQ9)*:** The shelf life was standardized to days. For each item, paired treatment and control values were extracted under identical storage conditions and marketing criteria. When multiple chitosan formulations or storage conditions were reported, each group was paired with its own control; storage at room temperature was prioritized when available. Meta-analyses and inferential tests were not applied due to heterogeneity between studies.

Main combinations of chitosan in postharvest (RQ10): The most common combinations of chitosan with other active compounds were identified. The data were organized by combination type, number of studies, specific agents included, and their application.

RESULTS AND DISCUSSION

Temporal evolution of scientific production (RQ1): The evolution of scientific production on the use of chitosan as a coating for post-harvest fruit preservation is characterized by exponential growth over time, grouped into four periods: Period I (1993–2000), Period II (2001–2008), Period III (2009–2016), and Period IV (2017–2025) (Figure 1). In Period I, only five documents were registered, although with a notable academic impact, accumulating 752 citations, suggesting a foundational role in this line of research. During Period II, a moderate expansion is observed with 33 publications and 4,893 citations, indicating a growth in scientific interest and greater visibility in the academic community. Period III reflects a thematic consolidation, with 185 documents and 14,275 citations, evidencing an accelerated maturation of the field. Finally, in Period IV there is a significant boom with 864 publications, accumulating 21,891 citations.

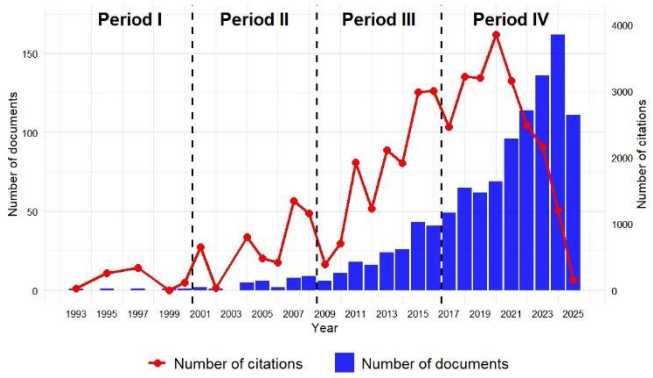

Figure 1. Temporal dynamics of the literature on chitosan coatings for postharvest fruit.

***Period I (1993–2000)*:** During this initial period, studies were published that addressed the application of edible coatings and biopolymers, including chitosan, in postharvest fruit preservation. In bananas, the action of different polymers and organic acids against *Colletotrichum musae* was explored, identifying formulations based on sucrose esters and fatty acids, as well as combinations with organic acids, as the most effective in reducing mycelial growth and the expansion of anthracnose lesions during storage (Al Zaemey et al., 1993). Furthermore, several authors conducted a review of minimally processed products, demonstrating the potential of edible coatings to reduce respiration, ethylene production, and microbial growth, thus extending the shelf life of cut fruits and vegetables (Baldwin et al., 1995).

Meanwhile, the effect of chitosan in controlling enzymatic browning and reducing the incidence of rot was studied in lychee fruits, where the coatings delayed the loss of anthocyanins and phenols, and decreased the enzymatic activity associated with browning (Zhang & Quantick, 1997a). Another study examined the use of polymeric films on minimally processed strawberries, indicating that chitosan films modified the internal gas composition and contributed to maintaining fruit firmness, although the shelf life was limited to six days (Yoo & Lee, 1999). Finally, authors evaluated the combination of *Candida saitoana* with glycolchitosan on apples (*Malus domestica* Borkh.) and citrus fruits, demonstrating that the joint formulation offered more effective control of rot under semi-commercial conditions than individual treatments, with results comparable to conventional fungicides such as thiabendazole and imazalil (El-Ghaouth et al., 2000).

Period II (2001–2008):

During this period, the authors expanded their research focus to a wider variety of fruits evaluated and in turn to the complexity of the formulations used. In this context, the studies covered tropical, subtropical and temperate species of commercial interest, including mango, papaya (*Carica papaya* L.), strawberry, pear (*Pyrus communis* L.), kiwi (*Actinidia deliciosa* [A.Chev.] C.F.Liang & A.R.Ferguson), table grape (*Vitis vinifera* L.), citrus (*Citrus* spp.), melon (*Cucumis melo* L.), pitahaya (*Selenicereus* spp.), lychee (*Litchi chinensis* Sonn.) and banana (Abbas et al., 2008; P. Chien et al., 2007; Eryani et al., 2008; Fisk et al., 2008; Hernańdez-Muñoz et al., 2008; Joas et al., 2005; J. Wang et al., 2007). During this period, innovative formulations were incorporated that combined chitosan with calcium, organic acids, polyphenols, ascorbic acid, carbonated salts, and natural antifungal agents such as natamycin, in addition to variants such as low molecular weight and irradiated chitosan (Chien & Chou, 2006; Hernańdez-Muñoz et al., 2006; Lin et al., 2008). Likewise, advanced methodologies were introduced, such as pre- and postharvest application and the use of nuclear magnetic resonance (MRI) to monitor ripening and deterioration (Galed et al., 2004). These approaches represented an advance compared to the previous period, by integrating combined strategies aimed at prolonging shelf life and preserving postharvest quality attributes.

Among the most notable works, studies that evaluated polysaccharide-based coatings including chitosan combined with modified starch, cellulose and lipid components in banana and mango stand out, which were more effective than commercial coatings in maintaining firmness, delaying acidity loss and reducing CO_2 evolution and weight loss, prolonging the quality and shelf life of the fruits (Kittur et al., 2001). Subsequently, chitosan was applied to citrus fruits to evaluate ripening and deterioration processes using nuclear magnetic resonance (MRI), demonstrating its effectiveness in reducing weight loss and preserving external appearance during storage under high humidity conditions (Galed et al., 2004). Browning control in lychee was addressed through combined treatments of chitosan with organic acids, observing that pericarp pH and weight loss directly correlated with the incidence of browning during storage (Joas et al., 2005). In Clementine mandarins, pre- and postharvest application of low concentrations of chitosan delayed peel pigmentation, reduced softening and decreased the incidence of water spot by up to 65%, without affecting internal ripening (Fornes et al., 2005).

On the other hand, authors in mango evaluated the efficacy of chitosan coatings with polyphenols, proving that this combination significantly reduced the loss of firmness and improved the sensory quality compared to the exclusive use of chitosan (Wang et al., 2007). Meanwhile, in fruits such as *Hami melon*, the use of coatings based on chitosan and polyethylene wax enriched with natamycin reduced the severity of rot and weight loss, while maintaining higher levels of ascorbic acid during storage at room temperature (Cong et al., 2007). In turn, in *Kinnow citrus*, the use of irradiated chitosan was introduced, reporting that it decreased the respiration rate and delayed changes in titratable acidity, sugars and vitamin C, maintaining the organoleptic quality for three months of cold storage (Abbas et al., 2008). Finally, the

application of chitosan coatings in combination with calcium was evaluated in strawberries, demonstrating that the joint formulations not only reduced the respiratory rate and weight loss, but also increased the firmness and calcium content in the fruits, with greater visual acceptance and absence of rot during the storage period (Hernańdez-Muñoz et al., 2008).

Period III (2009–2016):

In this period, unlike previous periods, research was characterized by the incorporation of complex formulations that combined chitosan with essential oils (oregano, thyme, lemon, clove, mint) (Barreto et al., 2016; Gol et al., 2015; Guerra et al., 2016; Perdones et al., 2016), phenolic extracts, natural antioxidant compounds (ascorbic acid, polyphenols) (X. Liu et al., 2016), biopolymers (pectin, alginate, gum arabic) and metallic or silica nanoparticles (Shi et al., 2013; Song et al., 2016), which enhanced their antifungal and antioxidant action. Likewise, innovative methodologies were introduced, such as the use of nanoparticles (Cindi et al., 2015), nanoemulsions (Sessa et al., 2015; Zahid et al., 2012) and advanced analysis techniques (electron microscopy, chromatography, gene expression) (Bazargani-Gilani et al., 2015; De et al., 2012; K. Liu et al., 2016), which allowed a more precise understanding of the mechanisms of action of the coatings. These innovations reflect the importance of chitosan not only as a physical barrier, but also as a bioactive matrix capable of modulating physiological and microbiological processes, with the goal of extending the shelf life and maintaining the post-harvest quality of fruits.

During this period, research focused on the contribution of fruits such as banana, where the authors evaluated the joint action of chitosan with 1-methylcyclopropene, demonstrating that the combined application delayed the loss of firmness, decreased the incidence of sugar spots and extended the shelf life by up to four additional days, with no negative effects on sensory characteristics (Báez-Sañudo et al., 2009). Meanwhile, in fresh cut mango, immersion in hot water followed by coating with chitosan inhibited microbial growth and allowed to maintain firmness and color for nine days of storage, confirming the value of combined heat and biopolymer treatments (Djioua et al., 2010). In the same species, nanomultilayer coatings based on pectin and chitosan were developed, which reduced weight loss, visual damage and microbial deterioration, indicating a positive effect on the gas barrier and on the extension of shelf life (De et al., 2012). On the other hand, in fruits such as grapes, chitosan combined with *Origanum vulgare* essential oil inhibited *Rhizopus stolonifer* and *Aspergillus niger*, in addition to preserving the physicochemical and sensory characteristics of the fruit, confirming the potential for synergies between biopolymers and natural antifungal compounds (Dos Santos et al., 2012). Likewise, in strawberries, the application of chitosan delayed qualitative and nutraceutical changes, reduced browning and stimulated antioxidant enzymes, improving the defense capacity of fruits against oxidative stress during refrigeration (Petriccione et al., 2015b). Complementarily, the use of chitosan nanoparticles loaded with *Cinnamomum zeylanicum* essential oil was introduced, which indicated sustained release, greater antimicrobial efficacy against *Phytophthora drechsleri* and extended the shelf life of cucumber up to 21 days (Mohammadi et al., 2015).

Additionally, in mango, coatings of different molecular weight were compared, observing that high molecular weight chitosan was the most effective in delaying ripening, maintaining titratable acidity, firmness and antioxidant activity, in addition to reducing the incidence of diseases during storage (Jongsri et al., 2016). In cherry tomato, the combination of chitosan with *Origanum vulgare* essential oil delayed the development of molds, decreased weight loss and preserved bioactive compounds such as phenolic acids, confirming the effectiveness of the synergistic approach in the control of fungal infections (Barreto et al., 2016). In blueberry, the combination of chitosan with *Aloe vera* extracts was tested for the first time, which allowed to reduce water loss by more than 40% and delay the appearance of fungal contamination by one week, extending the shelf life under refrigeration conditions (Vieira et al., 2016). Finally, in cucumber, a coating based on chitosan nanoparticles with essential oil of *Zataria multiflora* drastically reduced decomposition, improved antioxidant activity and extended storage life up to 21 days, consolidating the role of bioactive nanoformulations in postharvest (Mohammadi et al., 2016)

Period IV (2017–2025):

During this period, research focused on the incorporation of nanotechnology (Cai et al., 2025; T. Yan et al., 2025), hybrid biopolymers (W. Wang et al., 2024), nanocomposites such as ZnO (Indumathi et al., 2019), TiO_2 [74], CuO (Gunaki et al., 2024), silver (Shankar et al., 2021) and carbon quantum dots (Ezati et al., 2022), capable of improving the gas barrier and photoprotection, while layer-by-layer formulations (S. Ali et al., 2024) and smart coatings (Liang et al., 2025) allowed monitoring freshness and delaying senescence in highly perishable fruits such as strawberries, grapes, cherries, mangoes, guavas and citrus fruits. In parallel, bioactives of plant origin and agro-industrial by-products such as moringa extracts (Aghaei-Dargiri et al., 2025), mucilages (Q. Ali et al., 2024; Treviño-Garza et al., 2019), lignocellulosic residues (Ebrahimi et al., 2024) and new alternative sources of chitosan derived from insects (Guarnieri et al., 2024; Vitti et al., 2024) were integrated. Studies have shown significant effects in reducing rotting and modulating softening-associated enzymes (Rai et al., 2024; Wantat et al., 2021). Furthermore, the use of metabolomics, transcriptomics, and integrated analysis has shed light on how chitosan reprograms metabolic and antioxidant pathways to delay ripening and maintain firmness (Qiu et al., 2025; H. Yang et al., 2024; Zhou et al., 2024).

For this period, studies focused on the analysis of curcumin-loaded γ-cyclodextrin MOFs embedded in chitosan/gelatin,

which acted as respiratory and antioxidant nanochannels, doubling the mechanical strength and prolonging strawberry shelf life without loss of firmness or color (Cai et al., 2025). Likewise, smart chitosan/PVA systems with TiO_2 and anthocyanins added antimicrobial activity, UV blocking, and colorimetric signaling, even with surface cooling (~9.6 °C), achieving ≥10 days of conservation in bananas (~9,6 °C), logrando en banana ≥10 días de conservación (Liang et al., 2025). Furthermore, research focused on the use of carbon quantum dots obtained from by-products (e.g., banana peel, sericin), which improved vapor/oxygen barriers, preserved chlorophyll and ascorbic acid, and limited the microbiota in fruits and vegetables (Ban et al., 2025).

In parallel, the integration of ZnO with a marine antifungal (diaporthein B) in a chitosan matrix suppressed the advance of *Botryosphaeria dothidea* in apple (~65.5%) with proven biodegradability and safety (H. Du et al., 2025). In addition, chitosan-CuO (biosynthesized) coatings on mango reduced respiration and ethylene, maintaining AA = ascorbic acid, AT = titratable acidity and TSS = total soluble solids, with copper confined to the peel (T. Yan et al., 2023).

Furthermore, scientific advances focused on layer-by-layer coatings in mandarin, where the hydroxypropyl methylcellulose/chitosan sequence optimized gas permeability and preserved bioactives both at 20 °C and in cold conditions (Jurić et al., 2023). Moreover, high-performance plant biopolymers, such as water chestnut pericarp extract incorporated with chitosan, stabilized strawberry at ~20 °C reducing weight loss and softening (S. Kumar et al., 2025). Likewise, fenugreek mucilage films with rosemary essential oil extended apple shelf life up to ~30 days with antimicrobial action (Lindi et al., 2024). In terms of sustainability, insect-derived chitosan (*Hermetia illucens*) stood out against *Botrytis* spp. in strawberry, the non-decolorized fraction showed greater direct fungitoxicity, while the decolorized fraction acted as a defense elicitor (higher phenolic content) (Vitti et al., 2024). Finally, omics analysis in kiwifruit explains the physiological effect of chitosan by suppressing softening genes (AcPG1 and amylases such as AcBAM3L/AcBAM3.1) and modulating NAC/ERF/bHLH factors, which delays ripening and maintains firmness, starch and flavonoids (H. Yang et al., 2024).

***Geographical distribution by country (RQ2)*:** On a global scale, research on chitosan applied to post-harvest fruit preservation brings together contributions from 125 countries across five continents (Figure 2). Asia leads the production with 46.80% of the total. China (323 documents) and India (113) are the main hubs, followed by Iran, Indonesia, and Japan. The Americas are next with 25.12%, with the United States, Brazil, and Mexico standing out. Europe contributes 19.20%, with a significant presence from Italy, Spain, Turkey, and the United Kingdom. Africa contributes 5.14%, driven mainly by Egypt and South Africa, while Oceania, although with a smaller volume, adds 3.74%, mainly from Australia and New Zealand.

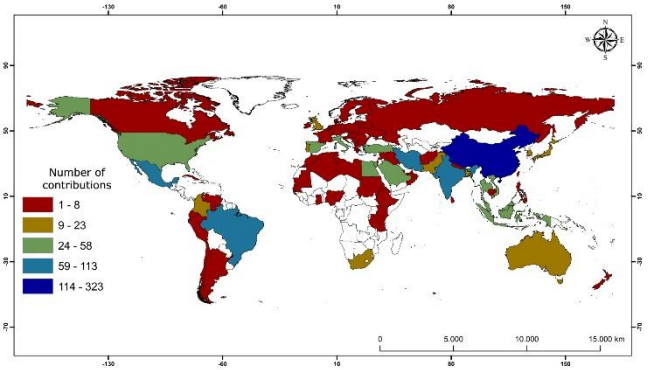

Figure 2. Geographical distribution of scientific production by country.

China is leading the research in chitosan-based postharvest coatings, with a clear emphasis on fruits such as strawberry, blueberry, mango, tomato, mandarin, orange, grapefruit, apple, pear, cherry, peach, kiwi, lychee, jujube, and banana. Scientific contributions particularly explore functional nanomaterials and advanced film architectures. Of note are MOFs/nanozymas (including γ-cyclodextrin-MOFs and IRMOF systems) (Mou et al., 2025; Y. Qin et al., 2025), photothermal/photocatalytic platforms (X. Yang et al., 2024), and metal oxides (TiO_2, ZnO, CuO, SiO_2/SiOx) integrated with chitosan to enhance gas barrier, UV blocking, and antimicrobial activity (Chang et al., 2024; K. Cheng et al., 2025; H. Du et al., 2025; T. Yan et al., 2023; Y. Zhu et al., 2019). Pickering emulsions are used to stabilize essential oils [103], humidity-regulating Janus films (C. Chen et al., 2025b), Janus films with humidity regulation (Dong et al., 2025) and layer-by-layer (LbL) designs are used to tune permeation and release (J. Yan et al., 2019). These include electrospun nanofibers (C. Cheng et al., 2023), double-network hydrogels (Zheng et al., 2025), ethylene scavengers (Fan et al., 2023) and colorimetric indicators to monitor freshness and suppress phytopathogens (X. Zhang et al., 2024).

Additionally, a marked orientation towards the incorporation of phytoactives and residues of agro-industrial origin was observed, such as polyphenols from apple and citrus peel (Asad et al., 2021; Riaz et al., 2018); extracts/essential oils of clove, thyme, cinnamon, rosemary or melaleuca (X. Zhang et al., 2025); polysaccharides (peach gum, konjac, ginkgo) (K. Sun et al., 2025); lignosulfonates from pulping (J. Zhu et al., 2024); arabinoxylans recovered from effluents (Bai et al., 2024); gelatin from fish flakes (J. Chen et al., 2025).

***Co-authorship and scientific collaboration networks (RQ3)*:** Analysis of the international research collaboration network identified a total of 68 countries linked through 218 unique cooperation pairs (Figure 3). Within this structure, China

emerged as the main node (88 links; 22.5% of the total), followed by the United States (49; 12.5%), Saudi Arabia (46; 11.8%), India (44; 11.3%), and Italy (40; 10.2%). Regarding the most intense bilateral collaborations, the Egypt–Saudi Arabia (23 records) and China–United States (16) axes stood out, followed by China–Saudi Arabia (9), China–Pakistan (8), and Indonesia–Japan (7). These links demonstrate a high level of dependence between certain countries. In the case of Egypt–Saudi Arabia, this relationship accounts for around 60% of all Egyptian collaborative output, reflecting a pattern of cooperation strongly concentrated on a single partner. Similarly, the China-US dyad accounts for approximately one-third of US production and about one-fifth of China's.

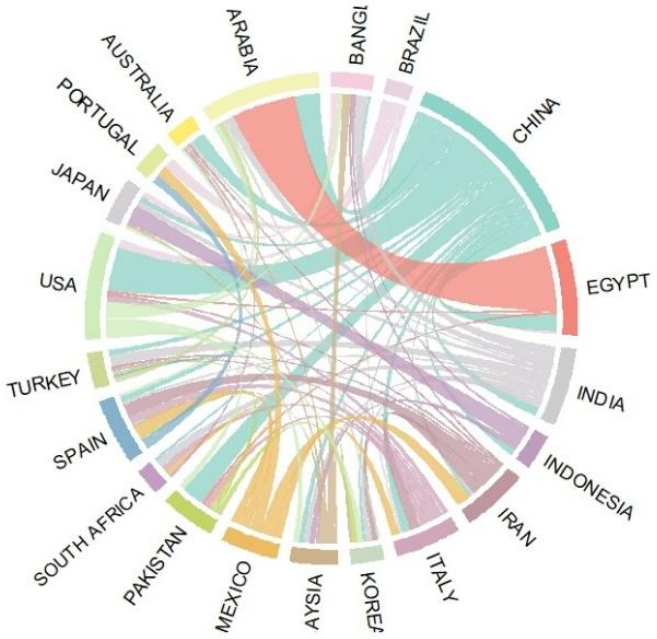

Figure 3. International network of co-authorship by country.

***More productive institutions (RQ4)*:** An institutional analysis of scientific production on chitosan coatings for postharvest fruit preservation reveals a marked geographic concentration in Asia and Latin America (Figure 4). The Ministry of Education of the People's Republic of China leads the ranking (21 publications), consolidating its strategic role in biopolymers and postharvest technologies. With 19 contributions each, Universiti Putra Malaysia, the National Polytechnic Institute (Mexico), and the Federal University of Paraíba (Brazil) are emerging as key regional hubs focused on sustainable solutions for the agroindustry. Likewise, the China Agricultural University (17) and the Ministry of Agriculture of the People's Republic of China (15) confirm the political and academic priority of this topic in that country. Completing the high-productivity group are Mansoura University (Egypt), Taif University (Saudi Arabia), Jiangnan University (China), and The University of Nottingham Malaysia Campus, with 12–14 articles.

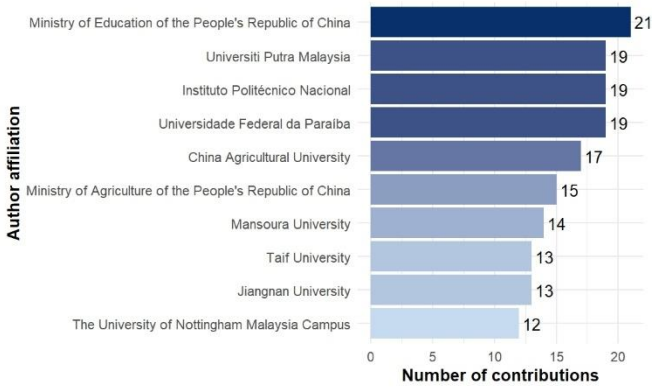

Figure 4. Institutions with the highest number of contributions.

Table 1. presents the leading institutions and their scientific contributions to postharvest chitosan coatings for fruits. Generally speaking, in Asia, the Ministry of Education and the Ministry of Agriculture of China, together with China Agricultural University and Jiangnan University, are leading the research in nanotechnology applied to edible coatings. Of note are nanozymes derived from metal-organic frameworks, Janus films with humidity regulation (Dong et al., 2025), photoactive bilayers sensitive to visible light (g-C3N4) (X. Yang et al., 2024), layer-by-layer assemblies tuned to fruit respiration and porous networks (COFs/MOFs) that transport antimicrobials such as silver nanoparticles of postbiotic origin, ε-polylysine or citral/linalool (Y. Du et al., 2022; Gao et al., 2024). Additionally, contributions focused on nanofillers and carrier systems (SiO_2, TiO_2, ZnO, carbon quantum dots, cellulose nanocrystals, β-lactoglobulin) are also highlighted) (Chang et al., 2024; M. Li et al., 2023; X. Wang et al., 2024; Y. Wang et al., 2025), with pre- and post-harvest combinations of calcium or 1-methylcyclopropene with chitosan (Qiuping & Wenshui, 2007); hot air or UV-C plus coating [122], and with biocontrol by antagonistic bacteria, in addition to non-destructive hyperspectral sensing (Y. Shao et al., 2021; Wen et al., 2024).

Meanwhile, in Latin America, the National Polytechnic Institute (Mexico) and the Federal University of Paraíba (Brazil) valorize by-products (coffee waste, acerola, jackfruit) (Andrea et al., 2025; A. C. A. Gomes et al., 2020; Rodrigues et al., 2018) and incorporate fungal chitosan and essential oils (mint, oregano, lemongrass) into composite matrices (Barreto et al., 2016; de Oliveira et al., 2020; Guerra et al., 2015). Meanwhile, Mansoura University (Egypt) and Taif University (Saudi Arabia) combine physiological cofactors (salicylic acid, epibrassinolide, Ca^{2+}) with inorganic nanoparticles (TiO_2/SiO_2) and controlled-release systems (EL-Gioushy et al., 2022; Lo'ay & Taher, 2018; Sami et al., 2021). Finally, in Malaysia, Universiti Putra Malaysia and The University of

Table 1. Leading institutions: fruits studied, technologies employed and main results .

Institution	Fruits	Technologies	Main results
Ministry of Education of the People's Republic of China	Strawberry, cherry, tomato, grape, kiwi, citrus, mango, apple, goji, jujube	Films/coatings with PVA and polycarbohydrates (konjac, carboxymethylglucan, pullulan/CMC); amyloid-like proteins; nano-TiO_2/SiO_2 (incl. nanoemulsion with clove); cellulose nanocrystals; COFs with biosynthesized AgNPs; MOFs (ZIF-L) + ε-polylysine; citral and essential oils	Less rotting, softening, and browning; greater firmness, titratable acidity, H_2O/O_2 barrier, and antimicrobial activity.
Universiti Putra Malaysia	Mango, papaya, banana, guava, carambola, tomato, cantaloupe, longan	Composites with gum arabic/starch; lignosulfonates; essential oils (cinnamon, thymol, vanillin) free or in nanoemulsion/nanoparticles; protein biofilms (spirulina, peptides)	Reduced rot and mass loss; improved firmness and color; delayed changes in TSS and AT; antioxidant preservation.
Instituto Politécnico Nacional	Blueberry, grape, tomato, cucumber, strawberry, pepper, papaya, fig, avocado, peach	Nanostructured coatings (often with PVA); essential oils (lemon, cinnamon/cinnamaldehyde, mint, thyme, α-pinene); residual extracts (coffee, Byrsonima, propolis); inorganic hybrids (boehmite-alumina); PLA/PBAT active packaging + pine oil	Control of Botrytis, Rhizopus, Alternaria, and Colletotrichum; longer shelf life; preserved firmness and color; maintained bioactive compounds.
Universidade Federal da Paraíba	Guava, mango, papaya, melon, grape, tomato	Chitosan + essential oils (lemongrass, Mentha, oregano, car-vacrol); gelatin-chitosan; zein + chitosan nanowhiskers; jackfruit seed starch; fungal chitosan (Mucor, Cunninghamella)	Inhibition of Colletotrichum, Rhizopus, Aspergillus, Lasiodiplodia, and Paramyrothecium; reduced losses; improved firmness, color, acidity, and phenols.
China Agricultural University	Kiwifruit, pear, apple, strawberry, nectarine, peach, grape, mango, lychee	Photoactive packaging (visible light); chitosan–silica; chitosan + cinnamon/thymol/banana peel polyphenols; molecular weight adjustment; chitosan–chlorogenic acid conjugate	Delayed deterioration; Penicillium control in pears; reduced wound damage and browning; extended shelf life at room temperature.
Ministry of Agriculture of the People's Republic of China	Strawberry, apple, pear, peach, grape, mango, tangelo, plum	MOF nanozymes; *Janus films* (humidity control); carbon quantum dots; carboxymethyl chitosan + linalool in β-lactoglobulin nanoparticles; LbL with graphene oxide; antibacterial multilayers; biomimetic sheet membranes; EVA film; antioxidant glazes	Decreased rot; preserved firmness and color; targeted volatile release; ROS modulation; non-destructive monitoring.
Mansoura University	Strawberry, banana, mango, blueberry, grape, guava, tomato, cucumber	Chitosan–PVA/PVP blends; co-adjuvants (24-epibrassinolide, salicylic, oxalic, gallic/gallate, ascorbic), nisin; chitosan/CMC-chitosan nanotransporters; NPs TiO2/SiO2/Zr-Mo; hot water + chitosan	Delayed ripening and browning; less rot and mass loss; reduced grape shattering; mitigation of chilling injury.
Taif University	Strawberry, blueberry, cantaloupe, mango, peach, apricot, cucumber, Barhi date	Chitosan nanoparticles and films; TiO_2/SiO_2; nisin, thymol; tea polyphenol nanoparticles; *Aloe vera*, $CaCl_2$, TPP	Superior shelf life and sensory acceptance; less rot and shrinkage; antioxidant enzyme activation; less chilling damage.
Jiangnan University	Cherry, pear, mango, cucumber, cherry tomato, longan, jujube	Double film (UV protection + antimicrobial); AgNPs + *Bacillus lipopeptide*; encapsulated citral (chitosan/carboxymethylglucan/PVA); visible light-activated g-C_3N_4 bilayers; LbL; self-healing coatings; MAP + chitosan; 1-MCP + chitosan; nanosilica	Reduced loss and darkening; increased firmness; photocatalytic microbial control with visible light (no UV).
The University of Nottingham Malaysia Campus	Papaya, banana, mango, cucumber, tomato, pepper	Chitosan + fish skin gelatin; gum arabic; lemongrass oil; black tea extract; chitosan-EO nanoemulsions; chitosan-surfactant ultrasound assemblies	Less anthracnose; stabilized firmness and color; more stable TSS and AT; improved antioxidant status; high acceptability.

Nottingham Malaysia Campus stand out for nanoemulsions and ultrasonic assemblies with gum arabic or fish skin gelatin, targeting sensitive tropical fruits (papaya, banana, mango) (Maqbool et al., 2010; Ranjith et al., 2022; Sekarina et al., 2023).

Most relevant scientific journals (RQ5): Table 2 summarizes and compares the journals with the highest production on postharvest chitosan coatings, demonstrating a clear concentration of higher impact Q1 journals (8 out of 10). The International Journal of Biological Macromolecules leads the

Table 2. Journals with the highest production and impact.

Journals	No. of contributions	Quartile	SJR	H-index	IF
International Journal of Biological Macromolecules	98	Q1	1,285	219	8,5
Food Chemistry	59	Q1	1,952	348	9,8
Postharvest Biology and Technology	50	Q1	1,363	178	6,8
Scientia Horticulture	41	Q1	0,889	155	4,2
Coatings	32	Q2	0,539	85	2,8
LWT	27	Q1	1,48	187	6,6
Foods	23	Q1	1,021	123	5,1
Journal of Food Measurement and Characterization	22	Q2	0,693	55	3,3
Food Hydrocolloids	21	Q1	2,837	235	12,4
Journal of the Science of Food and Agriculture	20	Q1	0,798	187	3,5

way (98 articles; IF 8.5; SJR 1.285; H-index 219), a hub for biopolymers and chitosan matrices; it is followed by Food Chemistry (59; IF 9.8; SJR 1.952; H 348) and Postharvest Biology and Technology (50; IF 6.8; SJR 1.363; H 178), which channel advances in food chemistry and postharvest physiology. In turn, Scientia Horticulturae (41; IF 4.2) reinforces the applied horticultural focus, while LWT (27; IF 6.6) and Foods (23; IF 5.1) provide a solid foundation in processes and technology in Q1. In parallel, Coatings (32; Q2; IF 2.8) and the Journal of Food Measurement and Characterization (22; Q2; IF 3.3) function as forums for functional coatings and analytical methodologies. Although with a smaller volume, Food Hydrocolloids (21; IF 12.4; SJR 2.837; H 235) stands out for its greater impact on hydrocolloid systems, and the Journal of the Science of Food and Agriculture (20; IF 3.5; Q1) broadens the agri-food perspective. Overall, the indicators (high SJR and H-index) confirm the maturity and visibility of the field, preferably published in leading journals with multidisciplinary scope and applied validation.

In this context, relevant scientific contributions stand out in the aforementioned journals: in the case of the International Journal of Biological Macromolecules, a document was published where it was found that chitosan film with banana peel extract improved the vapor barrier and antioxidant activity, preserving the apple better than chitosan alone and valorizing an agro-industrial by-product (W. Zhang et al., 2020). Meanwhile, authors in Food Chemistry showed that the combination of pre-harvest spraying and post-harvest chitosan coating on table grapes reduced rot and weight loss and modulated defense enzymes, with temperature-dependent responses (Meng et al., 2008). In turn, in Postharvest Biology and Technology, information was published highlighting that chitosan coating on sweet cherry activated antioxidant enzymes, contained browning and even delayed senescence (Pasquariello et al., 2015).

Similarly, a paper published in Scientia Horticulturae showed that 2% chitosan in guava maintained firmness and vitamin C, and increased the antioxidant capacity of the fruit (Hong et al., 2012). Likewise, authors in Coatings showed that a chitosan–pullulan composite enriched with pomegranate peel extract extended the shelf life of mango in both ambient and cold conditions, preserving sensory attributes and phenols (N. A. Kumar et al., 2021). In parallel, a contribution in LWT reported that a multilayered chitosan–pectin architecture with microencapsulated trans-cinnamaldehyde preserved color, β-carotene, and texture in fresh-cut papaya (Brasil et al., 2012). Furthermore, authors in Foods confirmed that 1–2% chitosan decreases dehydration and delays quality changes in strawberries, with dose- and cultivar-dependent effects (Petriccione et al., 2015b). In another contribution, in the Journal of Food Measurement and Characterization, the synergy of chitosan with thymol to improve firmness, color, and sensory acceptance and reduce rot in refrigerated figs was demonstrated (Saki et al., 2019). On the other hand, a research in Food Hydrocolloids presented chitosan films with essential oils and silver nanoparticles that, combined with gamma irradiation, decreased microbial deterioration and weight loss in strawberries (Shankar et al., 2021). Finally, researchers in the Journal of the Science of Food and Agriculture highlighted that chitosans of different molecular weights in fresh-cut papaya preserve color and firmness and reduce mesophilic flora, with greater efficacy of the average molecular weight (González-Águilar et al., 2009).

. *Most cited articles (RQ6)*: Table 3 lists the most influential articles on chitosan coatings in postharvest fruit processing and summarizes their main contributions. Among these papers, Hernandez-Muñoz et al. (2008) demonstrated in strawberries that coating with 1.5% chitosan alone or in combination with calcium gluconate suppresses rot for 7 days at 10 °C, reduces respiration, and limits mass loss and browning, thus pioneering the postharvest nutrition-barrier synergy. In turn, Han et al. (2004a) indicated that chitosan films enriched with calcium or vitamin E extend the shelf-life of strawberries and raspberries both under refrigeration and freezing, reduce rot and weight loss, reduce post-thawing dripping, and, innovatively, enrich the food (up to ~59 mg of Ca or ~7.7 mg of vitamin E per 100 g) without sacrificing the barrier function. Likewise, Gol et al. (2013) evidenced that, through hybrid formulations (carboxymethylcellulose–

Table 3. Top 10 most cited articles.

Authors	Title	Quotes
Hernández-Muñoz et al. (2008)	Effect of chitosan coating combined with postharvest calcium treatment on strawberry (*Fragaria* × *ananassa*) quality during refrigerated storage	485
Han et al. (2004b)	Edible coatings to improve storability and enhance nutritional value of fresh and frozen strawberries (*Fragaria x ananassa*) and raspberries (*Rubus ideaus*)	451
Gol, Patel & Rao (2013)	Improvement of quality and shelf-life of strawberries with edible coatings enriched with chitosan	423
Chien et al. (2007)	Effects of edible chitosan coating on quality and shelf life of sliced mango fruit	413
Jiang & Li (2001a)	Effects of chitosan coating on postharvest life and quality of longan fruit	406
Ali et al. (2011)	Effect of chitosan coatings on the physicochemical characteristics of Eksotika II papaya (*Carica papaya* L.) fruit during cold storage	402
Riaz et al. (2018)	Preparation and characterization of chitosan-based antimicrobial active food packaging film incorporated with apple peel polyphenols	397
Ribeiro et al. (2007b)	Optimization of edible coating composition to retard strawberry fruit senescence	380
Velickova et al. (2013)	Impact of chitosan-beeswax edible coatings on the quality of fresh strawberries (*Fragaria ananassa* cv Camarosa) under commercial storage conditions	355
Zhang & Quantick (1997b)	Effects of chitosan coating on enzymatic browning and decay during postharvest storage of litchi (*Litchi chinensis* Sonn.) fruit	345

Chitosan and hydroxypropylmethylcellulose – Chitosan), phenols and anthocyanins, crucial for the inhibition of cell wall enzymes involved in softening, are preserved.

In ready-to-eat fruit, chitosan coating (0.5–2%) on cut mango reduced water loss, maintained flavor and appearance, increased sugars (soluble solids), acidity, and vitamin C, and inhibited microorganisms; most importantly, it offered a simple and applicable procedure for minimally processed products (Chien et al., 2007). On the other hand, a clear dose-dependent effect was observed in longan fruit (*Dimocarpus longan*): less respiration and weight loss, delayed browning, and less rot, showing that chitosan not only acts against microbes but also helps regulate fruit physiology (Y. Jiang & Li, 2001b). Finally, in papaya, chitosan coating decreased dehydration, preserved firmness, delayed color change, and sugar rise, supported by sensory tests and internal gas balance (CO_2/O_2); Overall, it provides a solid foundation for commercial use (Ali et al., 2011).

In by-product valorization, Asad et al. (2018) innovated by incorporating apple peel polyphenols into chitosan films, obtaining a material with high antioxidant and antimicrobial activity, lower water vapor permeability, and adequate mechanical performance at low loads, opening a sustainable path for active packaging. Methodologically, Ribeiro et al. (2007a) advanced from empirical formulation to physicochemical optimization: they characterized wettability, surface tension, and oxygen permeability of starch, carrageenan, and chitosan coatings, identified optimal compositions, and, including $CaCl_2$, demonstrated in the laboratory and field that carrageenan-calcium and chitosan-calcium minimize firmness and mass loss, in addition to reducing microbial load.

On the other hand, Veličkova et al. (2013) evaluated wax-chitosan-wax multilayer architectures in strawberry, which decreased senescence, dehydration and respiration, and preserved color and texture. Finally, Zhang & Quantick (1997a) demonstrated in lychee that chitosan (1–2%) modulates browning by attenuating polyphenol oxidase and peroxidase, stabilizing phenols and anthocyanins, and reducing dehydration and decay.

Keyword co-occurrence analysis (RQ7): Figure 5 illustrates the word co-occurrence map constructed from 147 items, organized into 5 clusters and connected by 1,475 links. The most frequently occurring term is chitosan (n = 438), followed by edible coating (139) and shelf life (129); also notable are coating (85), quality (63), postharvest (62), and edible coatings (58).

Cluster 1 (Red color): Post-harvest quality and edible coatings: This cluster brings together directly applied coatings on fruit based on chitosan alone or blended with conventional biopolymers (alginate, pullulan, pectins, gelatin, caseinates, HPMC, PVA) (Firdaus et al., 2024; Sul et al., 2023; Taktak & Kaya, 2025; Xu et al., 2023). Through soft crosslinks (tannin/Fe^{3+}, citrate, dialdehydes) and polymeric reinforcements (e.g., crystalline cellulose), these matrices adjust the permeability and microatmosphere of the surface without resorting to nanotechnology (Jia et al., 2025; W. Jiang et al., 2025; Sani et al., 2024). Functionality is optimized with essential oils and phenolic extracts in low-complexity emulsified formulations and with compatible handling strategies (modified atmosphere/CO_2, soft UV, Ca^{2+} pretreatments) (de Menezes et al., 2024; Rezaiyan Attar et al., 2023). The results converge in shelf life extension and maintenance of physicochemical and sensory attributes (reduced rot and mass loss; stable firmness and color), which supports its scalability and sustainability.

Cluster 2 (Green color): Nanotechnology and bioactive coatings: Here, nano-enabled chitosan systems are grouped together, incorporating inorganic NPs (ZnO, TiO_2, Ag, CuO) with antimicrobial effects; MOFs/COFs as controlled-release reservoirs of volatiles (thymol, linalool, curcumin); and carbonaceous nanomaterials (carbon dots, graphene/MXene)

for photoprotection or photodynamic antibacterial action (Taghipour et al., 2024; Tavassoli et al., 2024; W. Wang et al., 2024; T. Yan et al., 2023). Nanoemulsions and Pickering are used to stabilize essential oils, cyclodextrins/proteins as carriers, and nanoreinforcements (nanocellulose, montmorillonite, nanostructured chitosan) that reduce permeability and increase mechanical strength (Andrea et al., 2025; C. Cheng et al., 2023; Das et al., 2023; Nkede et al., 2023; Reis et al., 2023). In the form of ultra-thin films, sprayable coatings or electrospun fibers, these devices show lower microbial incidence and better conservation in a wide range of fruits, with low doses of active ingredients and clear alignment with the circular economy (Fan et al., 2023; Na et al., 2024; C. Qin et al., 2023).

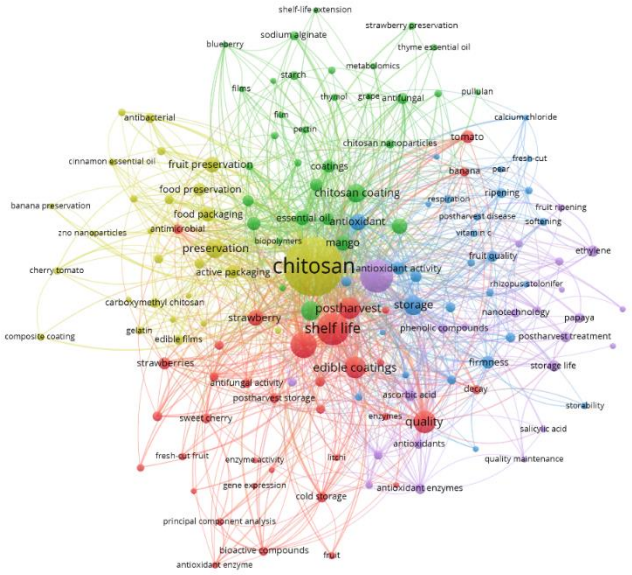

Figure 5. Keyword co-occurrence network.

***Cluster 3 (Purple color)*: *Physiology and post-harvest diseases*:** This cluster focuses on fruit response mechanisms modulated by chitosan coatings. Different models show delayed ripening and softening via regulation of the cell wall and the oxidative system, as well as reduced browning and water loss and adjustments in TSS/AT and volatiles (S. Ali et al., 2024; Husnayain et al., 2025; X. Shao et al., 2012; W. Zhang et al., 2019). In parallel, protection against phytopathogens (*Botrytis* spp., *Alternaria* spp., *Penicillium* spp., *Colletotrichum* spp., *Rhizopus* spp.) has been documented through active matrices (emulsified, cross-linked) or physiological cofactors (Ca, putrescine, salicylic acid, melatonin, aloe) and synergies with modified atmosphere or UV light, which translates into greater tolerance to chilling damage and less functional deterioration without the need to describe the architecture of the packaging (Hajebi Seyed et al., 2021; Y. Jiang et al., 2022; H. Li et al., 2024; Meng et al., 2008; D. Wang et al., 2022).

Cluster 4 (Yellow color)*: *Active and intelligent packaging: In this cluster, chitosan is integrated into biodegradable packaging systems with active and intelligent functions designed for whole or minimally processed fruit. Biopolymers (starch, alginate, pullulan, gelatin, cellulose/nanocellulose, lignin) and controlled crosslinks (tannin–Fe^{3+}, citrate, vanillin dialdehyde) are combined with nanophases (ZnO/TiO_2/CuO, biogenic silver, MOF/COF, silica, carbon dots, graphene/MXene) to provide antimicrobial activity, photoprotection, and humidity/gas regulation (Javed et al., 2025; W. Liu et al., 2023; Qiu et al., 2025; Tan et al., 2025; Venkatesan et al., 2024). Notable among these are Janus films (Dong et al., 2025), photoactive coatings (e.g., g-C_3N_4, Prussian blue) (Ołdak, 2025), anthocyanin-based colorimetric indicators, and CO_2 monitoring devices for fresh cuts (Husnayain et al., 2025; Liang et al., 2025). Together, these packages reduce decay, browning, and weight loss, maintain firmness and color, and allow for monitoring.

***Cluster 5 (Blue Color): Antioxidants and bioactive compounds*:** This cluster addresses chitosan coatings enriched with natural antioxidants applied directly to fruit. Research highlighting the use of phenols and polyphenols (gallate, protocatechuate, proanthocyanidins, resveratrol, curcumin) (Jia et al., 2025; Yu et al., 2024; Zhou et al., 2023), essential oils (cinnamon, clove, thyme, ginger, peppermint), and redox cofactors (mango/grapefruit/hibiscus/rosehip peel extracts, Ginkgo or kombucha polysaccharides) (Alamer et al., 2025; Asif et al., 2025; Stefanowska et al., 2025; K. Sun et al., 2025) formulated as conjugates, microcapsules with β-cyclodextrin, or protein–polysaccharide blends (gelatin, caseinates, pectin, pullulan) (Mou et al., 2025; Ponnusamy et al., 2025; J. Sun et al., 2023) for sustained release. Its action is manifested in the capture of ROS, reduction of MDA, stabilization of membranes and modulation of signals (salicylic, putrescine, melatonin, NO), with preservation of polyphenols, color and sensory properties in cold and at room temperature (Gürler, 2023; Lv et al., 2023; X. Zhang et al., 2024).

***Most studied fruits (RQ8)*:** Figure 6 illustrates the distribution of the number of articles that have evaluated the use of chitosan in fruits of agricultural interest. *Fragaria* × *ananassa* Duch (strawberry) is the most investigated fruit, with a total of 132 studies, which represents the greatest focus on the use of chitosan for fruit preservation. It is followed by *Mangifera indica* (78), *Solanum lycopersicum* (76), *Vitis vinifera* (46) and *Carica papaya* (41), all of them climacteric fruits of high commercial value, which require effective post-harvest handling strategies. Significant contributions are also observed for *Musa* spp. (38), *Malus domestica* (33) and *Psidium guajava* (31). Fruits such as *Pyrus communis* (27), *Prunus avium* (25), *Vaccinium* spp. (20), *Citrus reticulata* Blanco (20) and *Citrus* × *sinensis* (17), while others such as

Cucumis melo (13), *Prunus persica* (11), and *Capsicum annuum* (14) have been less studied so far.

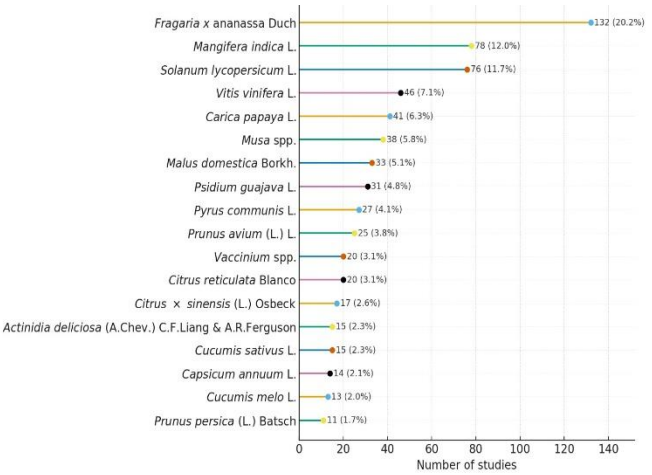

Figure 6. Most studied fruits with postharvest chitosan applications .

These data indicate that chitosan has been preferentially explored in vulnerable fruits during postharvest: prone to mechanical damage and accelerated deterioration (high respiration/transpiration or sensitivity to ethylene), with relevant incidence of specific phytopathogens (e.g., *Botrytis* spp., *Colletotrichum* spp., *Rhizopus* spp. and *Penicillium* spp., depending on the species) and with fragile tissues and thin cuticle, conditions that favor dehydration and physiological damage.

***Effect of chitosan on postharvest shelf life (RQ9)*:** Figure 7 demonstrates a significant increase in storage life for all fruits evaluated when chitosan was applied. The highest values were recorded for *Citrus* × *sinensis* (30.91 days), *Pyrus communis* (21.44 days), and *Mangifera indica* (18.72 days), compared to their respective controls, which only reached 17.5, 7, and 12.25 days, respectively. On average, fruits treated with chitosan had a shelf life 1.5 to 3 times longer than controls. This pattern is shown for *Vaccinium* spp. (14.81 vs. 5.66 days), *Capsicum annuum* (18.71 vs. 10.33 days), and *Carica papaya* (15.8 vs. 5.8 days). Chitosan treatment proved effective in maintaining the postharvest quality of the fruits tested, which typically have a high respiration rate and are susceptible to damage. These results indicate that chitosan is a sustainable strategy for extending storage life and reducing postharvest losses in a wide range of fruit species.

In strawberries, chitosan coatings with *Thymus capitatus* essential oil applied by immersion and stored at 5 °C prolonged shelf life compared to the control: at 15 days, the rotting index was 5.8–9.2% compared to 45% of the control, with less mass loss, attenuated respiration, and a delay in the increase in pH and soluble solids; additionally, a reduction in aerobic mesophiles and molds/yeasts and better preservation of antioxidant capacity were observed. Sensory acceptance was higher with intermediate concentrations of the oil, while high doses altered aroma and flavor, which supports optimizing the formulation to balance efficacy and sensory quality (Martínez et al., 2018b).

In the study by Rokayya et al. (2021), a marked difference in postharvest preservation of blueberries treated with chitosan-based coatings compared to untreated fruits (control) was observed. Over the 8 days of storage at room temperature, chitosan-coated fruits showed less weight loss, firmness retention, and higher ascorbic acid contents, which contrasts significantly with the control, which showed a rapid deterioration rate, reaching 44.45% rot incidence at the end of storage. These results indicate that chitosan acted as a semi-permeable barrier, limiting transpiration and physiological decomposition, while providing antifungal protection that extended the fruit's shelf life.

In another study of blueberries treated with chitosan coating at 5°C, it was shown that chitosan was able to completely inhibit the growth of mesophilic bacteria and fungi for 14 days, while in control fruits, significant proliferation of microorganisms was observed as early as the seventh day. This difference demonstrates chitosan's ability to act as an antimicrobial barrier, limiting microbial deterioration and prolonging the fruit's shelf life. Even at 10°C, chitosan remained effective for the first five days, in contrast to the control, which showed a rapid loss of microbiological quality (Sun et al., 2014).

In mango fruits, recent studies confirm that coating with chitosan (750–1500 ppm) reduces weight loss by 44–50% (storage in open containers) and 51–65% (storage in zip-lock bags); it also decreases microbial load (total bacterial count) by 52–73% compared to the control and controls mold (total mold and yeast counts). In terms of quality, the coating preserves vitamin C and titratable acidity and delays sugar accumulation, consistent with a barrier effect that modulates gas exchange and ripening (Parvin et al., 2023).

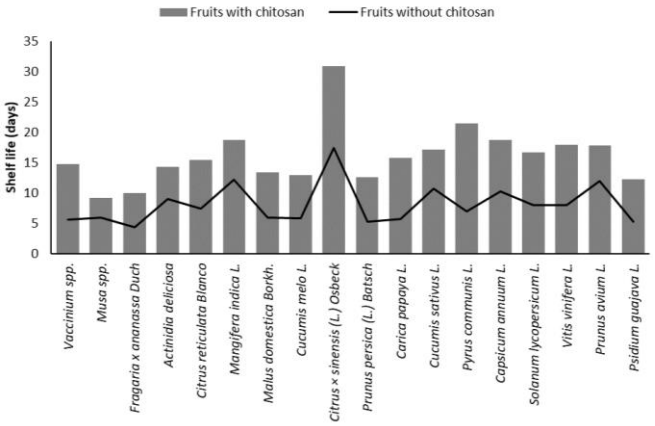

Figure 7. Shelf life (days) with chitosan (bars) vs. without chitosan (line) across fruit species.

Table 4. Main combinations of chitosan in postharvest .

ChitosanCombination	No. of studies	Specific agents included	Main application
Chitosan + Essential Oil	90	Lemongrass, cinnamon, thyme, clove	Postharvest fruit preservation
Chitosan + inorganic nanoparticles	89	ZnO, CuO, Ag	Antimicrobial activity and barrier properties
Chitosan + Gelatin	15	bovine, fish	Functional biofilm formation for postharvest preservation
Q + PVA (Polyvinyl Alcohol)	15	β-acids (hops), β-cyclodextrin, HE-β-cyclodextrin	Synthetic polymer / Structural reinforcement
Chitosan + Calcium Chloride	16	$CaCl_2$	Maintains firmness and reduces softening
Chitosan + Pectin	12	Pectin	Development of edible coatings and biodegradable films for fruit

In bell pepper (*Capsicum annuum* L), an *in vitro/in vivo* study indicated that chitosan coatings at 1.0–2.0 g L^{-1} completely inhibited mycelial growth and sporangia germination of *Phytophthora capsici*. In inoculated fruit, these concentrations reduced incidence and severity to 0%, eliminated visible lesion areas, and preserved fresh and dry weight compared to the control. After 9 days at 26 °C, weight loss was 11.5–11.8% with 1.0–2.0 g L^{-1}, compared to 23.7% in the control. The authors link this effect to the direct antifungal action of chitosan (cation–membrane interactions that destabilize the fungal cell) and to its function as a semipermeable film that modulates gas exchange (Torres-Rodriguez et al., 2025).

***Main combinations of chitosan in postharvest (RQ10)*:** Table 4 summarizes the main combinations of chitosan with other compounds applied in the postharvest field. Six frequent combinations were identified, the most reported being chitosan with essential oils, with a total of 90 studies. This combination includes natural agents such as lemongrass, cinnamon, thyme, and clove, and is predominantly used in fruit preservation due to its antifungal and antioxidant properties. The second most reported combination is with nanoparticles (n = 89), particularly metal oxides such as ZnO, CuO, and Ag, recognized for improving the antimicrobial activity and barrier properties of coatings. Other relevant combinations include chitosan with gelatin (n = 15), of bovine or fish origin, aimed at the formation of functional films; as well as chitosan with polyvinyl alcohol (PVA) (n = 15), used as a structural reinforcement and as a matrix for active compounds such as β-acids and cyclodextrins. Also noteworthy is the use of calcium chloride (n = 16) in conjunction with chitosan, the main objective of which is to maintain fruit firmness and reduce softening during storage. The combination with pectin (n = 12) has been applied to develop edible coatings and biodegradable films, in line with current sustainability trends.

In banana, a nanoemulsion of lemongrass (*Cymbopogon citratus*) essential oil encapsulated in chitosan nanoparticles showed high antioxidant capacity and antimicrobial activity against *Bacillus cereus* and *Escherichia coli* (disk diffusion). In bananas (stage 2 of maturity) coated by immersion and stored for 11 days, firmness, pH, loss of mass and color (CIE Lab* and RGB) were monitored, observing a delay in ripening, better maintenance of firmness and less browning compared to the control (Putra et al., 2025b). In strawberry, 2% chitosan coatings enriched with *Thymus capitatus* essential oil (0.5–1.5%) applied and stored for 15 days at 5 °C reduced damage caused by molds/yeasts and a lower drop in antioxidant capacity (ABTS) and better quality preservation(Martínez et al., 2018b).

In tomato, a coating of chitosan-copper nanoparticles (0.01–0.04%) extended storage to 21 days at room temperature by reducing rot, decreasing physiological weight loss, maintaining greater firmness, and lowering the respiration rate. It also contained the increase in TSS and sugars, preserved titratable acidity and ascorbic acid, inhibited PPO, and maintained color. Electron microscopy revealed a "nano-mesh" on the fruit surface that acts as a barrier to microbial infection, moisture loss, and gas exchange. (Meena et al., 2020).

In papaya (*Carica papaya* L.), the application of 1% chitosan, 4% gelatin, a chitosan+gelatin mixture, and layer-by-layer assembly (chitosan as a sublayer + gelatin as a coating) showed that gelatin and layer-by-layer were the most consistent in preserving quality: lower mass loss, greater firmness, and better color stability at 5 °C. In terms of composition, these coatings contained the increase in soluble solids and maintained minimal acidity variations, while layer-by-layer preserved vitamin C with greater stability than the other formulations. There was an increase in catalase at the end of storage in the mixture and layer-by-layer, suggesting additional antioxidant protection. The use of protein (gelatin) + polysaccharide (chitosan), especially in layer-by-layer, extended the shelf life to at least eight days under refrigeration, surpassing chitosan alone (Silva et al., 2023).

***Conclusions*:** This study demonstrates that research on postharvest chitosan coatings has moved from an exploratory phase to a consolidation stage, with exponential growth since 2017. Production is concentrated in Asia, with China as the main node and intense but asymmetric collaboration networks; dissemination occurs mainly in Q1 quartile journals (SJR) with strong participation from nanotechnology-oriented institutions.

The intellectual structure is organized around four axes: low-complexity edible coatings, bioactive nanoenablement, postharvest physiology/ diseases, and antioxidants/ phytoactives. Postharvest chitosan studies focus on strawberries, mangoes, tomatoes, grapes, and papayas, and collectively report longer shelf lives, 1.5 to 3 times longer than untreated fruits. The most studied combinations are chitosan + essential oils and chitosan + nanoparticles.

This work provides useful information for decision-making in research and development and technology transfer: it guides the selection of chitosan formulations based on the technological objective and the species, and supports the implementation of alternatives with the greatest proven increase in shelf life.

Based on the evidence compiled, it was demonstrated that the application of chitosan alone or in combination is a safe and sustainable strategy for reducing postharvest losses and preserving fruit quality.

***Acknowledgement*:** To UTEQ for supporting this investigation

CRediT author statement*:** Herrera-Feijoo, J. Torres-Rodriguez J.A. Carranza-Patiño, M.S. Chicaiza-Ortiz, C. Guamán-Rivera, S.Toulkeridis, T. Hernandez-Montiel, L.G. ***completed the experiments; Herrera-Feijoo, J. Torres-Rodriguez J.A. Carranza-Patiño, M.S. Chicaiza-Ortiz, C. Guamán-Rivera, S.Toulkeridis, T. Hernandez-Montiel, L.G. ***prepared the draft*** Herrera-Feijoo, J. Torres-Rodriguez J.A. Carranza-Patiño, M.S. Chicaiza-Ortiz, C. Guamán-Rivera, S.Toulkeridis, T. Hernandez-Montiel, L.G *reviewed and finalised the draf*.

***Conflict of interest*:** *The authors did not have economic funding*

Ethical statement: This article does not contain any studies which require ethics committee approval.

***Availability of data*:** The data is available with the corresponding author which can be made available on request.

***Consent to participate*:** All participants consented for this research study

***Informed consent*:** All participants consented for this research study.

***Consent for publication*:** All participants consented for this research study.

***SDGs addressed*:** No poverty, Zero hunger, good health and well-being

***Policy referred*:** Ecuador's National Climate Change Strategy (ENCC), National Policy for Sustainable Livestock Development.

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